

CARBON NANOTUBE FIELD EMISSION AND ITS APPLICATIONS TO SPACE EXPLORATION

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INTRODUCTION

Why carbon nanotube (CNT) field emission for space exploration?

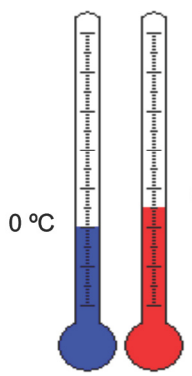
- Electronics for extreme environment
- Miniature analytical instruments for *in situ* application
- High frequency (THz) sources for radiometry



EXTREME ENVIRONMENT



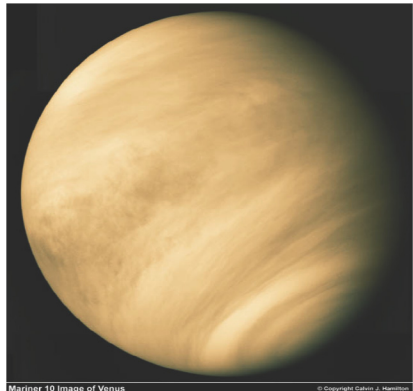
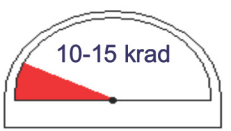
Earth Orbiter



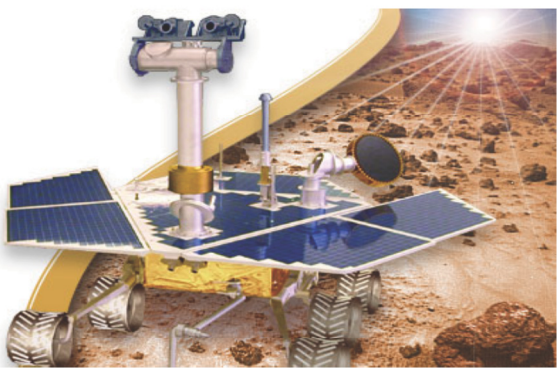
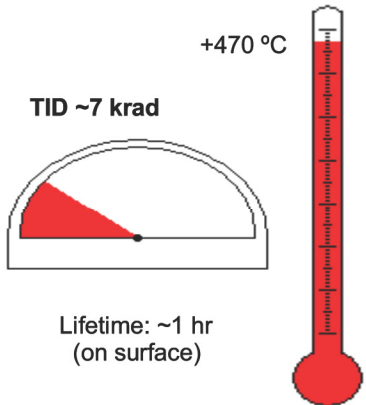
TID



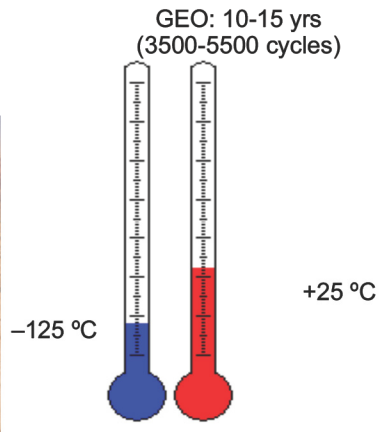
LEO: 1-3 yrs
(500-1500 cycles)



Venus



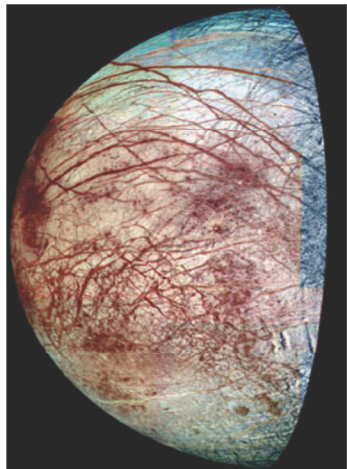
Mars Rover



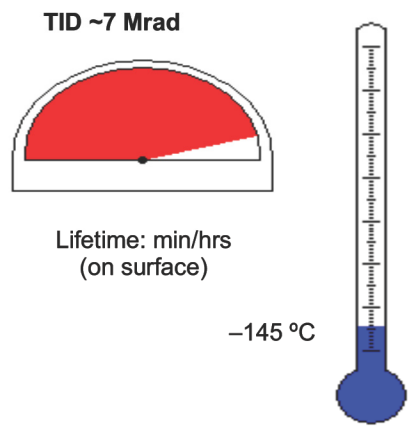
GEO: 10-15 yrs
(3500-5500 cycles)



Lifetime: 90 days



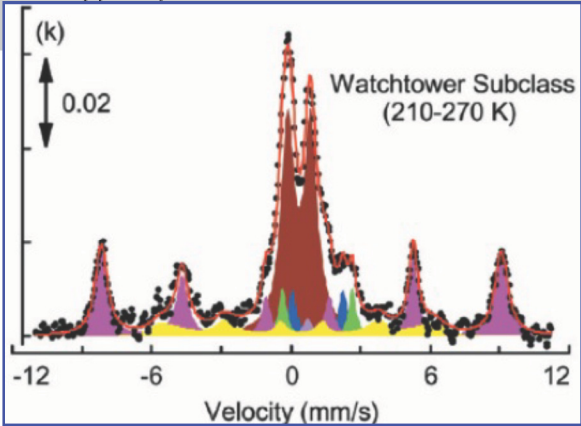
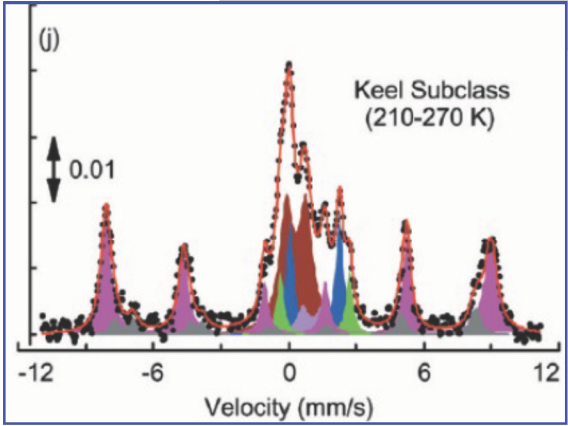
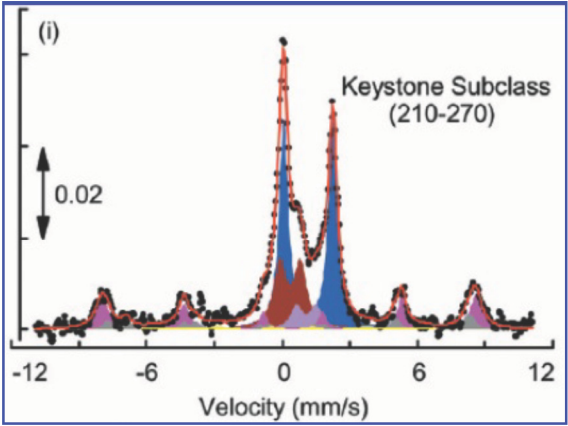
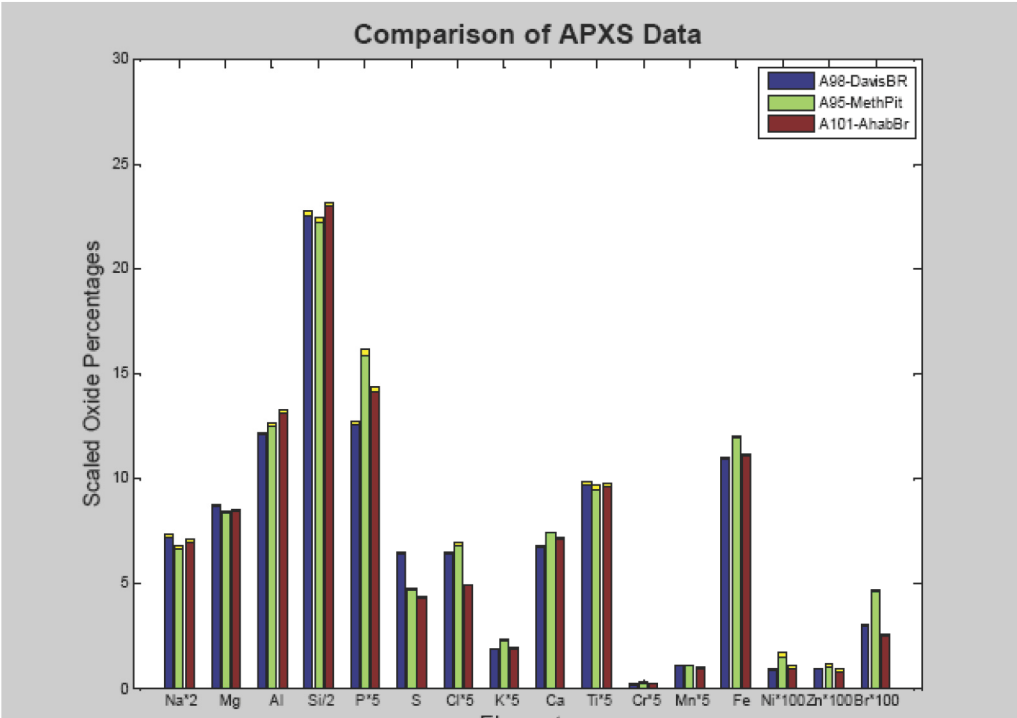
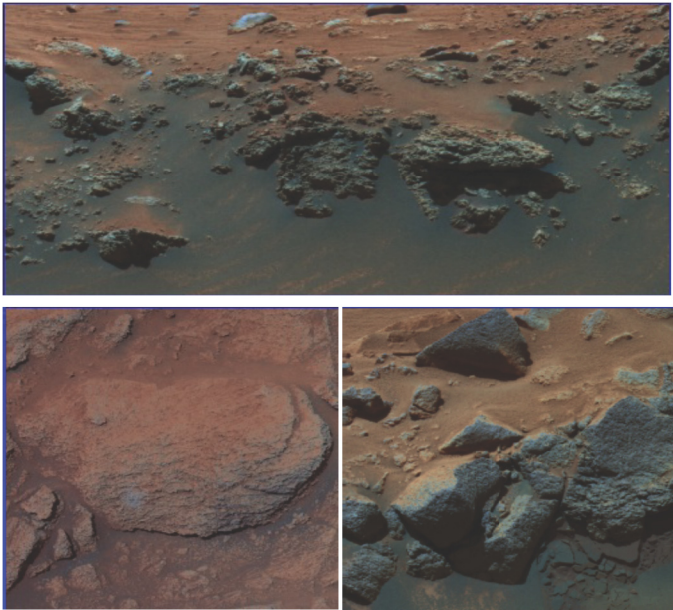
Europa



MINIATURE ANALYTICAL INSTRUMENTS



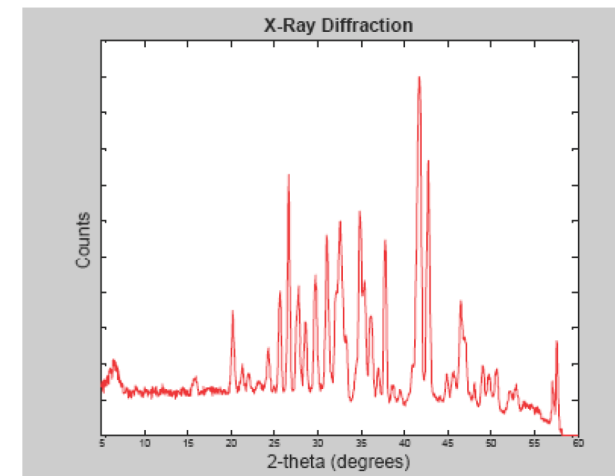
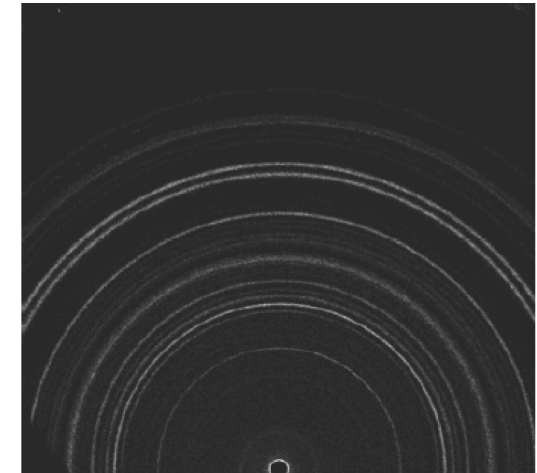
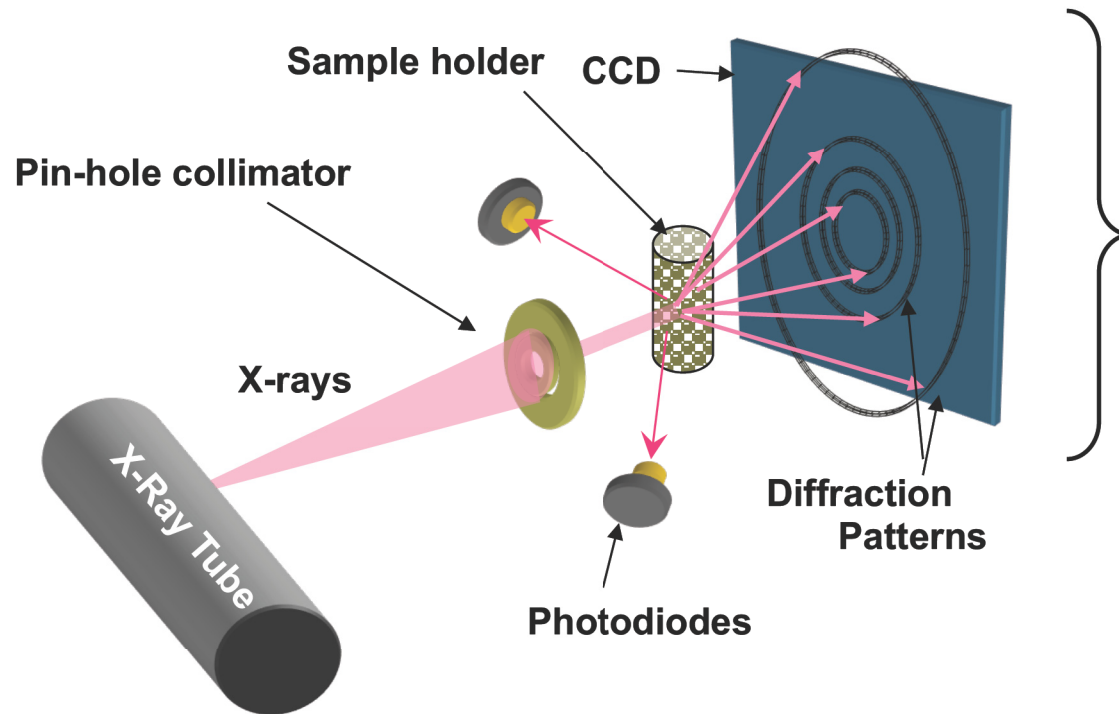
The Importance



Courtesy: A. Yen (JPL)

MINIATURE ANALYTICAL INSTRUMENTS

High efficiency, miniature X-ray sources



Design conceived/developed by **Dr. D. Blake et al** of NASA-Ames (sketch is influenced by Dr. Blake's concept).

Schematic is somewhat similar to the CheMin instrument on Mars Science Laboratory (**CURIOSITY**).

Why CNTs?

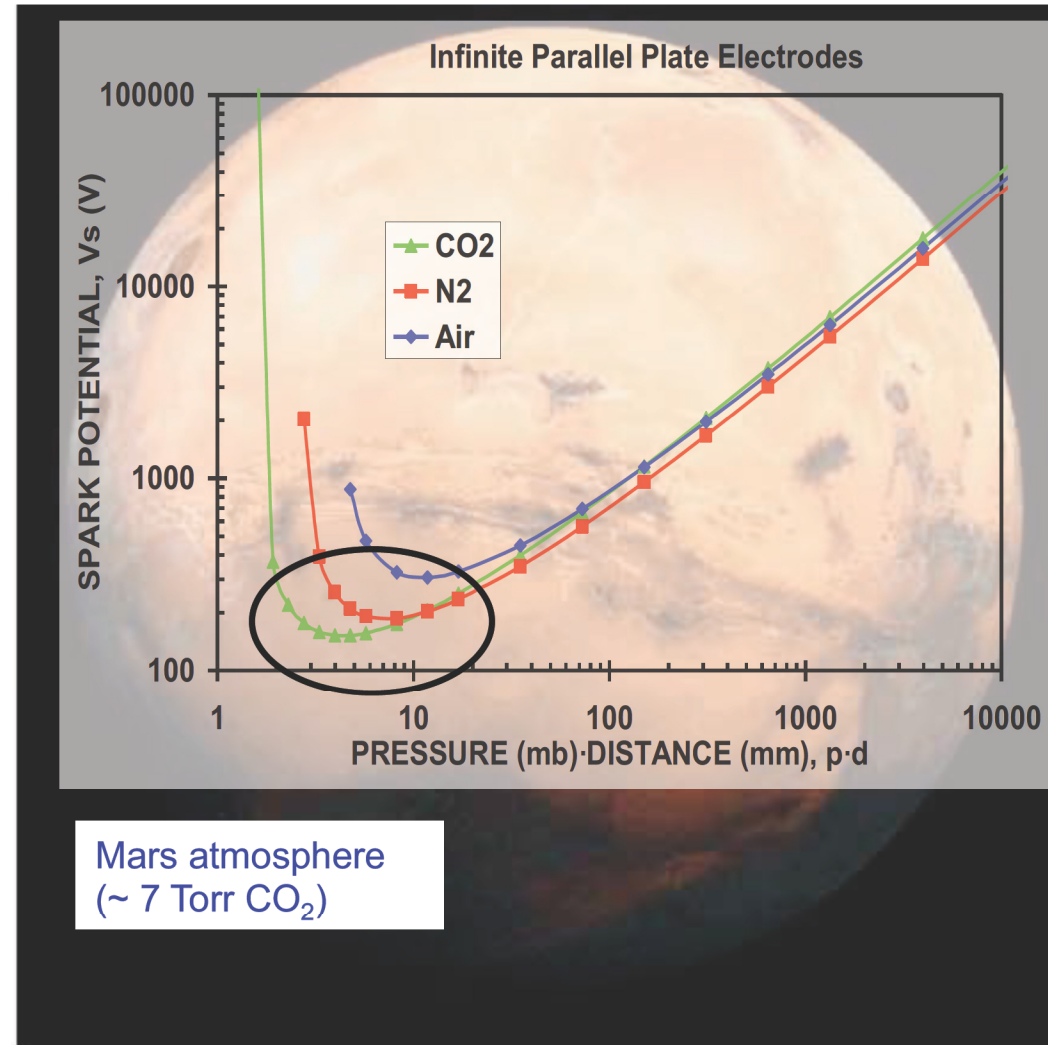
Obvious reasons

- **No heater:** Save on power, mass, volume
- **Small source:** Easier focusing >> Smaller spot size >> Sharper diffraction patterns

Not obvious but of high importance

- **Lower Voltage of Operation:**
15 kV in stead of 30 to 50 kV!

Important on Mars!



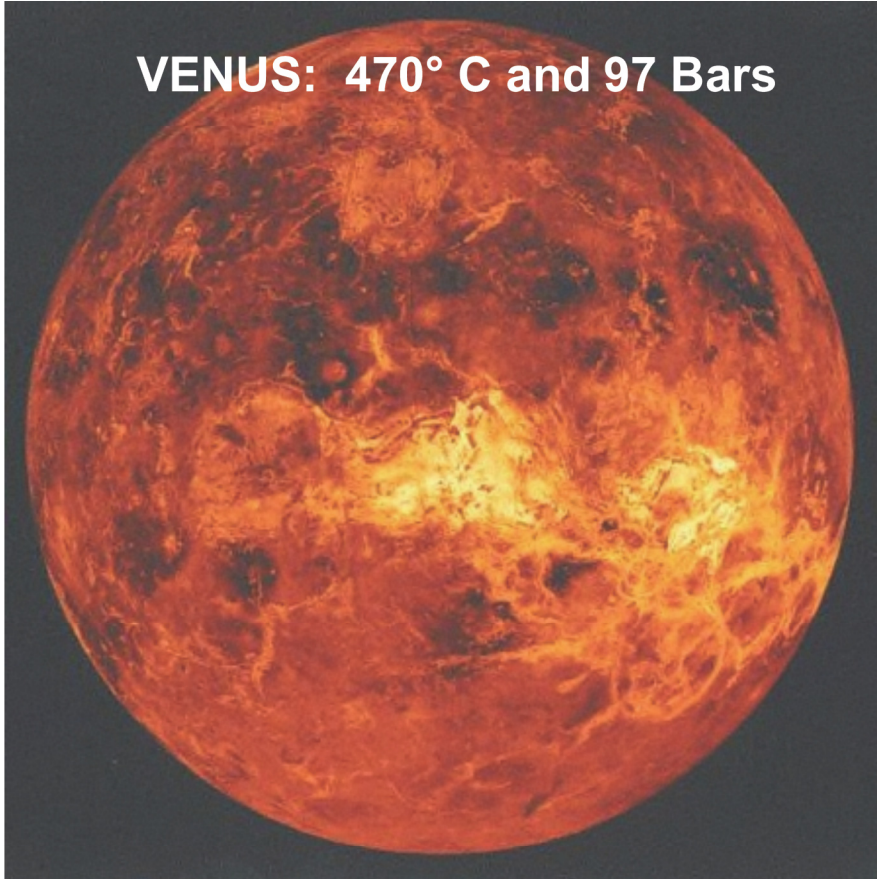
HVPS for a miniature X-ray tube is a challenge!

MINIATURE ANALYTICAL INSTRUMENTS



How does high-current density help?

VENUS: 470° C and 97 Bars



Estimated integration times on Mars ranges from 1 to 10 hours (Mission life times of months to years).

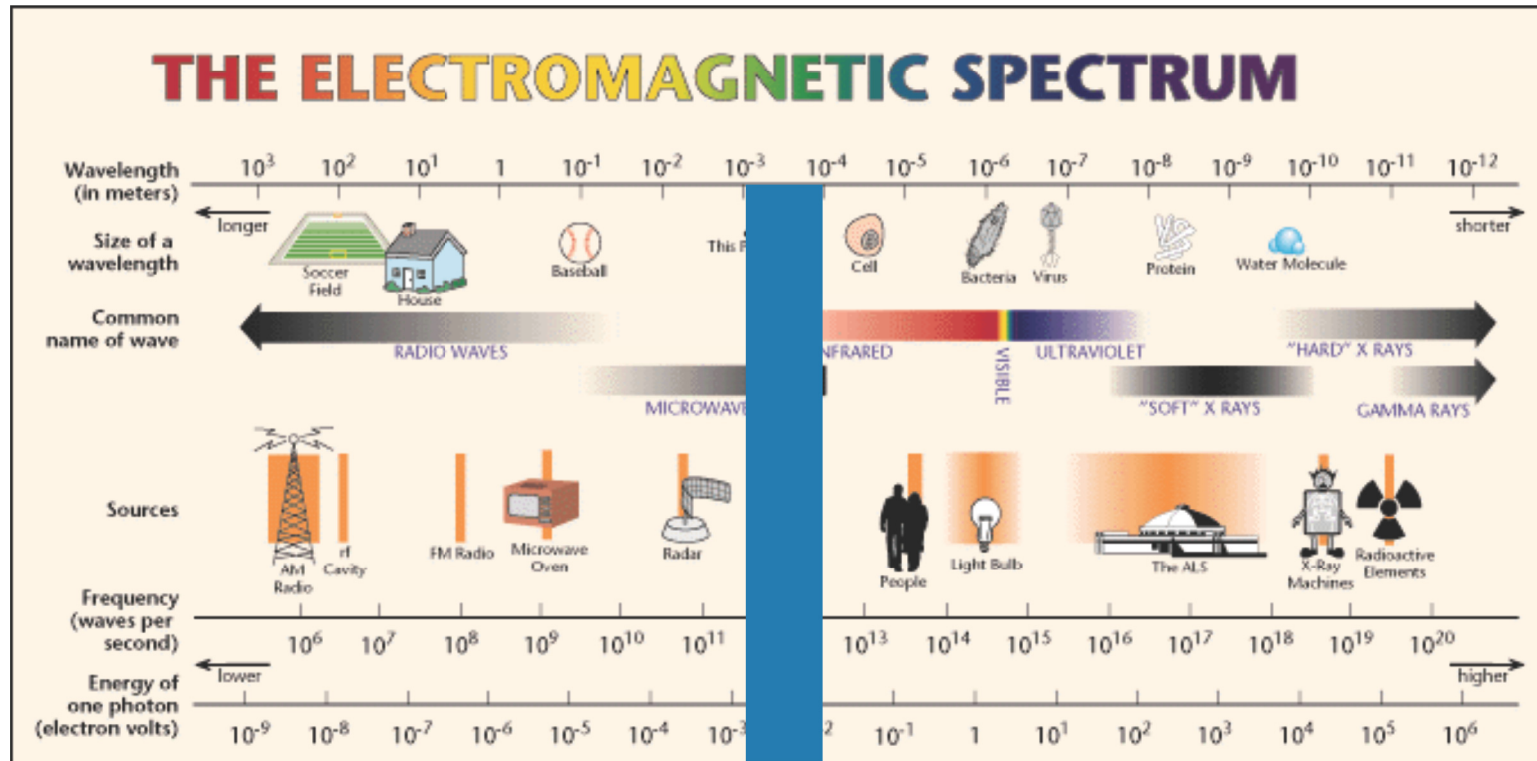
For landed missions on Venus anticipated mission life time it self is 5 to 10 hours!

Potentially the mission can start and end in the same press briefing!

Need for faster data collection rates: Possible when CNT X-ray tubes are employed (data collection rate is detector limited).

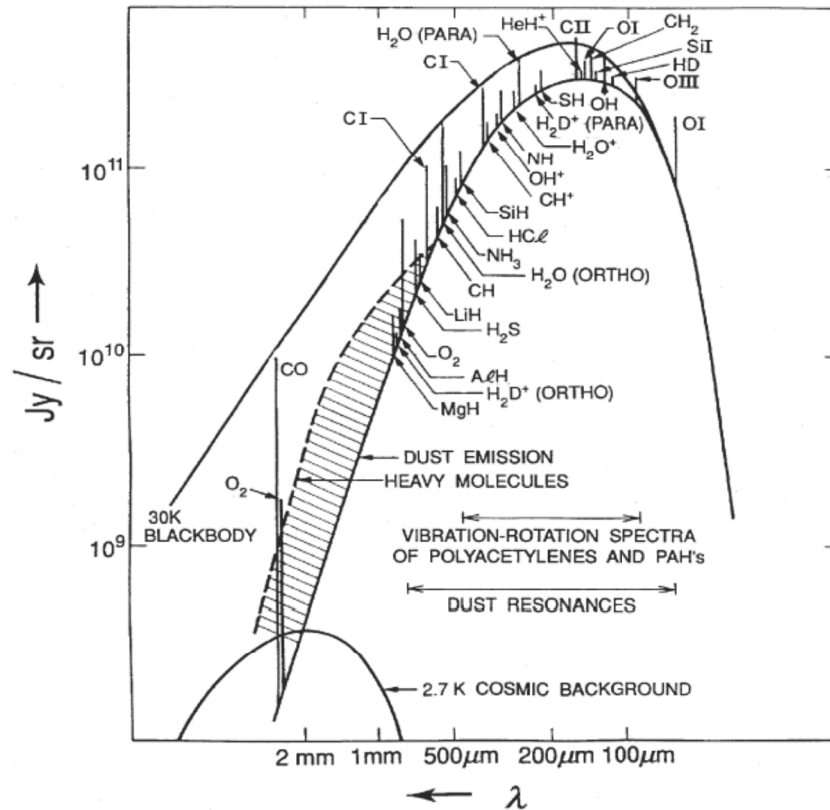
HIGH FREQUENCY SOURCES

Submillimeter Wave or Terahertz region



300 GHz to 3 THz (1000 mm to 100 mm)

HIGH FREQUENCY SOURCES

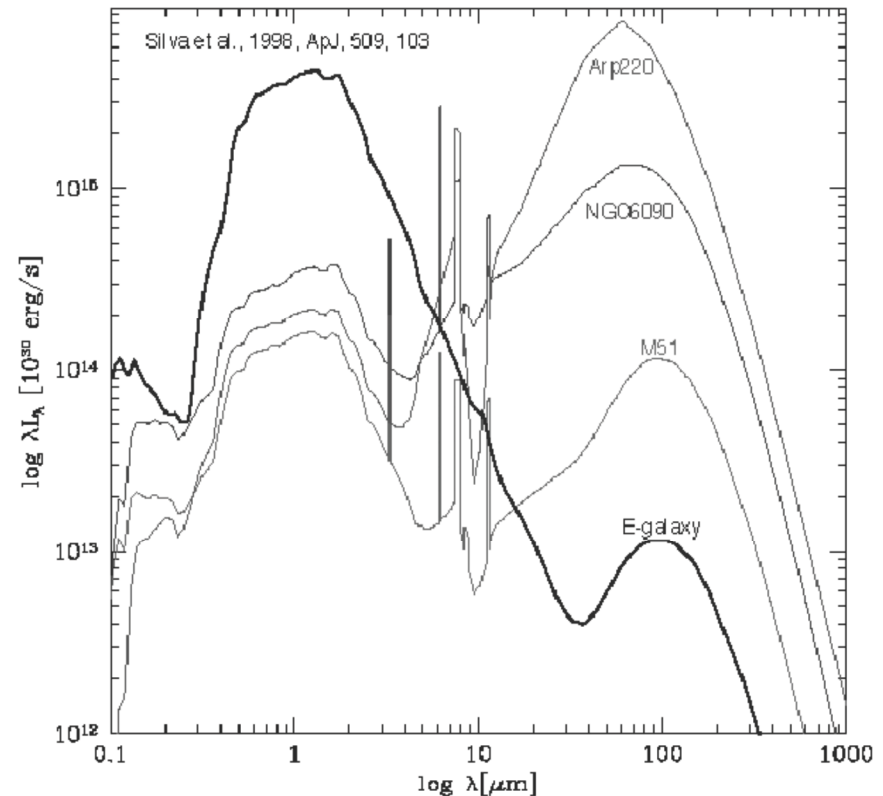


Key molecular emission lines in the THz region (Radiated energy vs. Wavelength)

Ref: T.G. Phillips, J. Keene, "Submillimeter astronomy," Proc. IEEE, vol 80, pp1662-1678, Nov. 1992

Magnitude of energy output in THz region used to determine the age of galaxies (E-galaxy, the youngest and Arp220, the oldest)

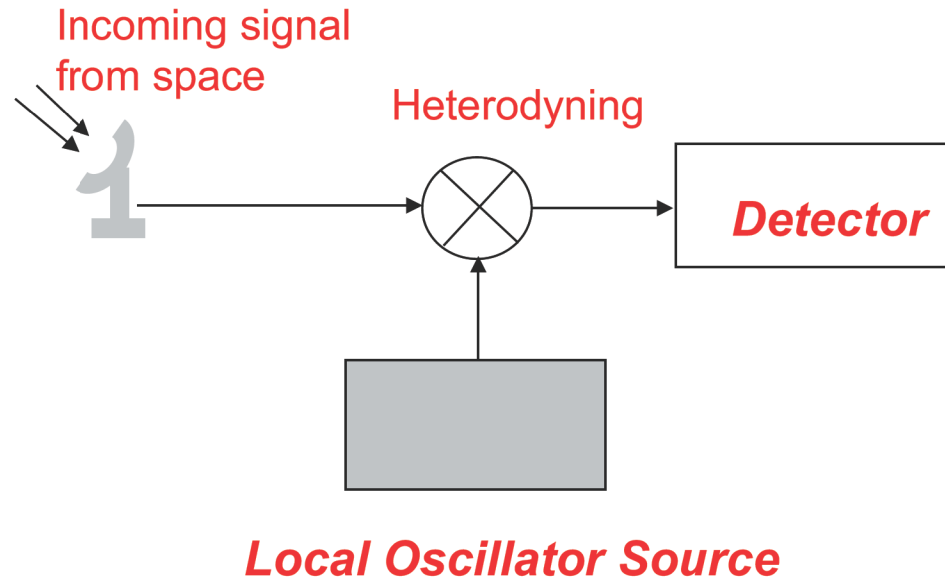
Ref: P.H. Siegel, "THz Technology," IEEE Transactions on Microwave theory and Techniques, vol. 50 (3), pp. 910-928, Mar. 2002



HIGH FREQUENCY SOURCES

THz radiation is used to determine the composition of planetary and stellar matter, remotely.

High-resolution heterodyne spectroscopy

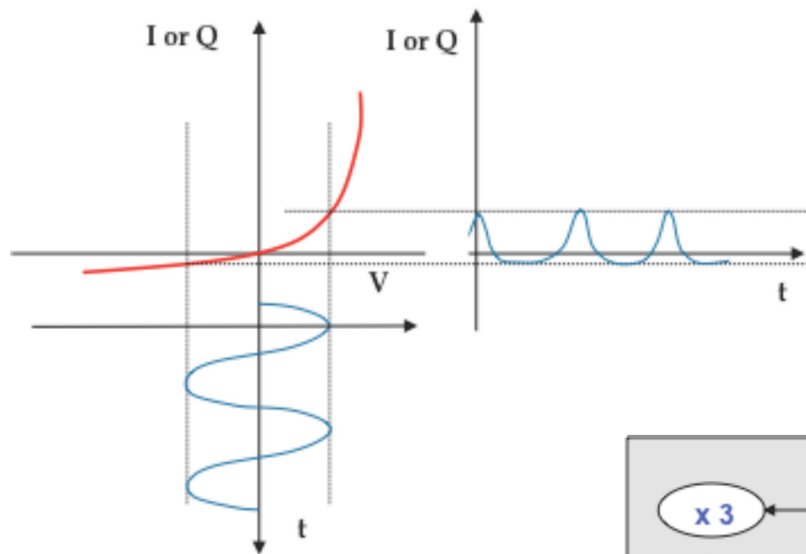


Heterodyning enhances the signal to noise ratio.

HIGH FREQUENCY SOURCES

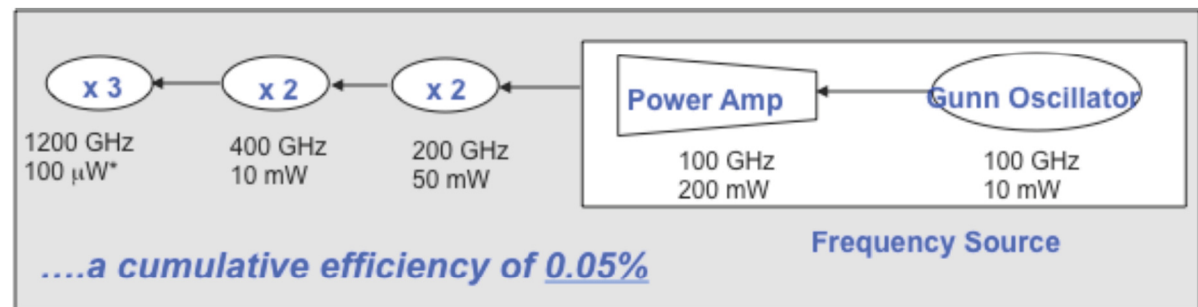
State-of-the-Art THz Sources

The most widely used THz sources are non-linear reactance based (solid-state Schottky diode) frequency multiplier chains.



$$I(t) = I_0 + I_1 \cos(\omega t) + I_2 \cos(2\omega t) + \dots$$

$$Q(t) = Q_0 + Q_1 \cos(\omega t) + Q_2 \cos(2\omega t) + \dots$$



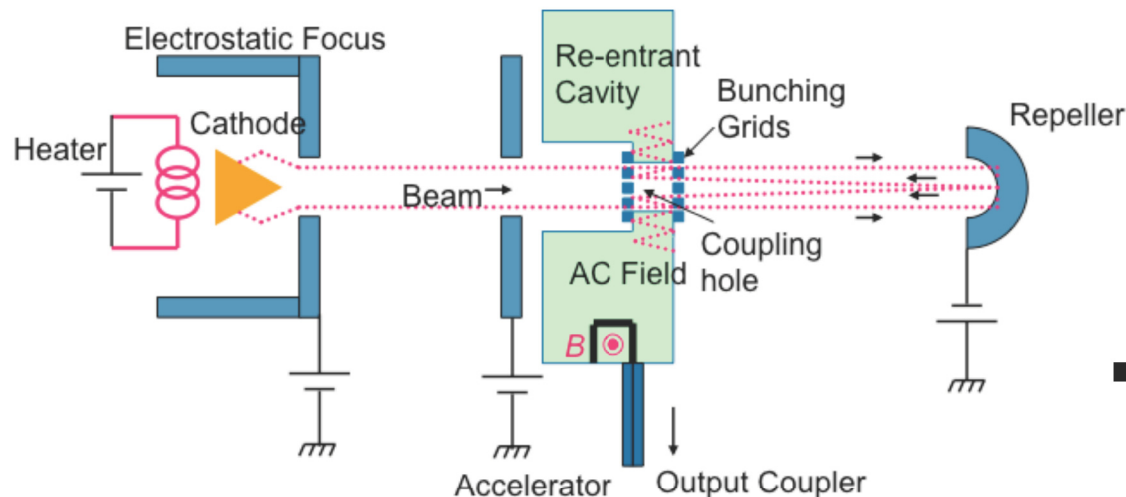
...highly inefficient as the multiplication factor increases (> 4)

Typical Local Oscillator Source

* Power shown is a JPL result. All measurements were conducted at room temperature

HIGH FREQUENCY SOURCES

CNTs enable miniature vacuum tube sources



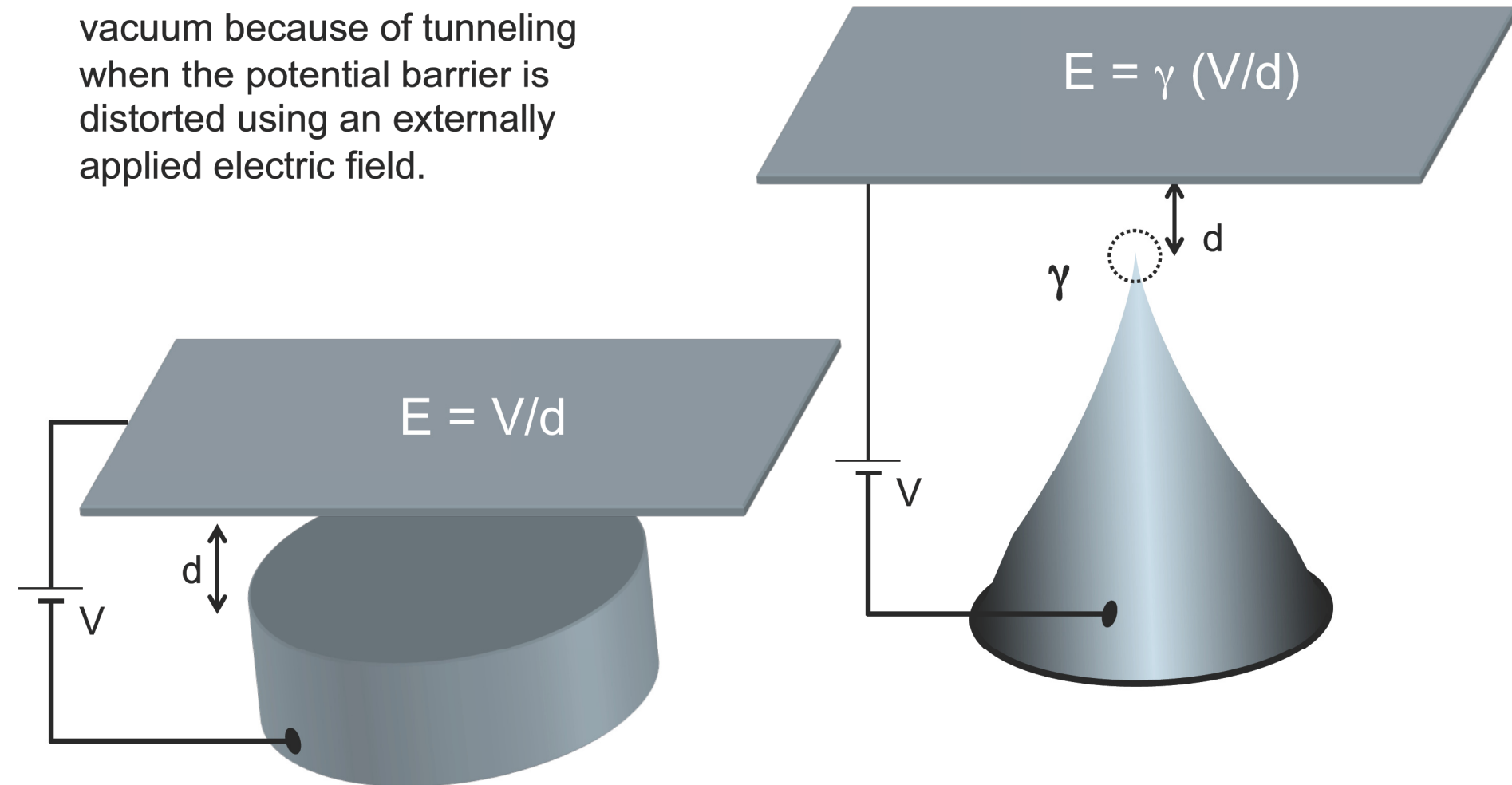
- Vacuum tube amplifiers:
 - *Traveling Wave Tubes (TWTs)*
 - *Backward Wave Oscillators (BWOs)*
- Klystrons
 - *Klystrino (Scheitrum)*
 - *Nanoklystron (Manohara & Siegel)*

Resonating cavity dimensions are inversely proportional to the designed output frequency

FIELD EMISSION OF ELECTRONS

Principle

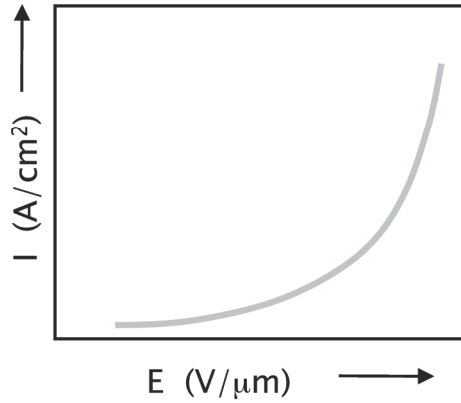
Emission of electrons into vacuum because of tunneling when the potential barrier is distorted using an externally applied electric field.



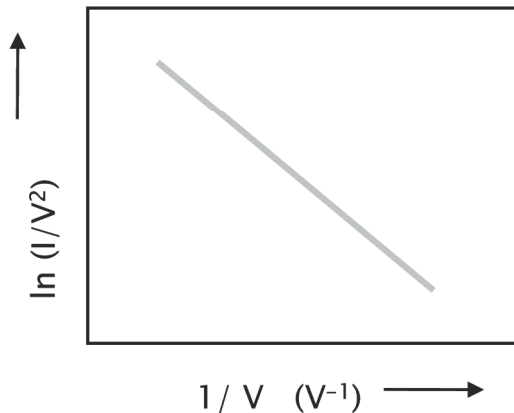
FIELD EMISSION OF ELECTRONS

Fowler-Nordheim Equation

I-V Curve



Fowler-Nordheim Curve



$$I = 1.54 \times 10^{-6} \frac{\gamma^2 A_{(e)}}{\phi} \cdot \left(\frac{V}{d} \right)^2 \cdot e^{\left[-6.8 \times 10^7 \cdot \frac{\phi^{3/2} \cdot d}{\gamma V} \right]}$$

$$\ln \left(\frac{I}{V^2} \right) = \ln(a) - \frac{b}{V}$$

$$I \propto \gamma^2$$

“ γ ” is the key!

I : Emission current (A)

V: Biasing voltage (V) ; d : gap

a, b: constants

ϕ : Work function

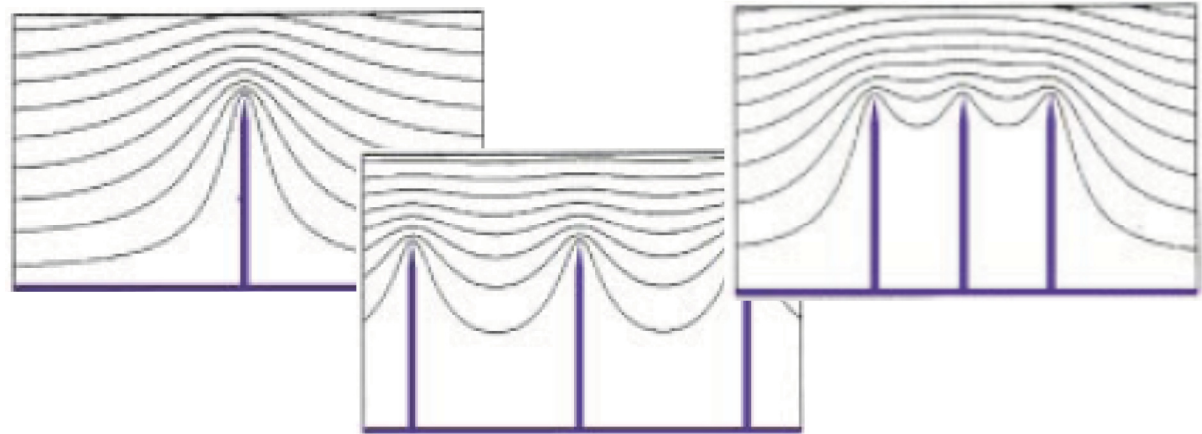
γ : Field enhancement factor

$A_{(e)}$: Emission area

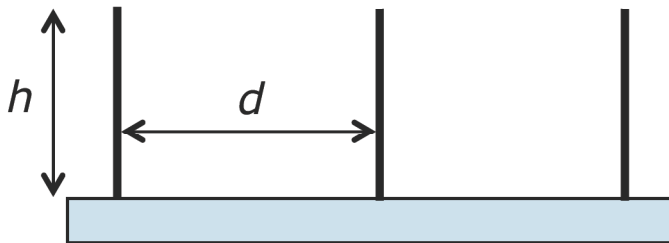
FIELD EMISSION OF ELECTRONS

Simulation of field
penetration

by L. Nilsson *et al*
APL 76(15) 2071-2073 (2000)



$$I \propto \gamma^2 \Rightarrow \begin{cases} \gamma \propto \text{Aspect Ratio (reciprocal of the tip radius)} \\ \gamma_s \propto \text{Reciprocal of CNT number density} \rightarrow \text{For the sample} \end{cases}$$



$$d = 2h \text{ (simulation)}$$

L. Nilsson *et al*, APL 76 (15), 2071-2073 (2000)

$$d = h \text{ (experiment)}$$

J.S. Suh *et al*, APL, 80, 2392-2394 (2002)

Achieving high-current density is really an OPTIMIZATION problem.



FIELD EMISSION OF ELECTRONS

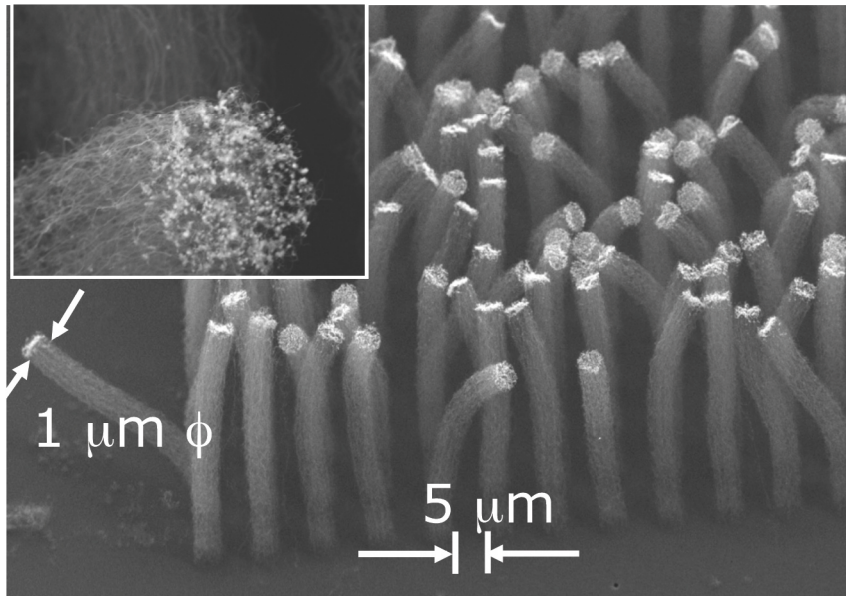
High electron emission from a single CNT (30 to 100 nA) does not scale up with increased number of CNTs on a sample.

Electrostatic screening and number density limit emission levels.

CNTs tolerate poor vacuums better than other options- good for application in miniature systems (10^{-5} to 10^{-6} Torr).

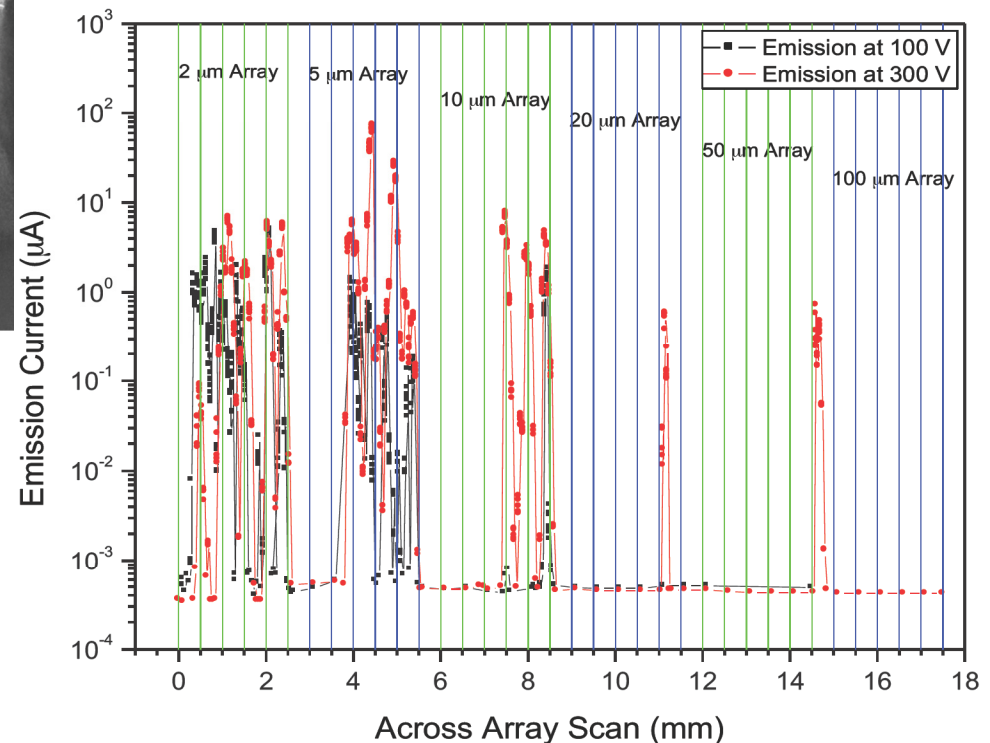
Optimum arrangement of CNTs to maximize the emission current density- researched by many groups

HIGH-CURRENT DENSITY CNT BUNDLE ARRAYS



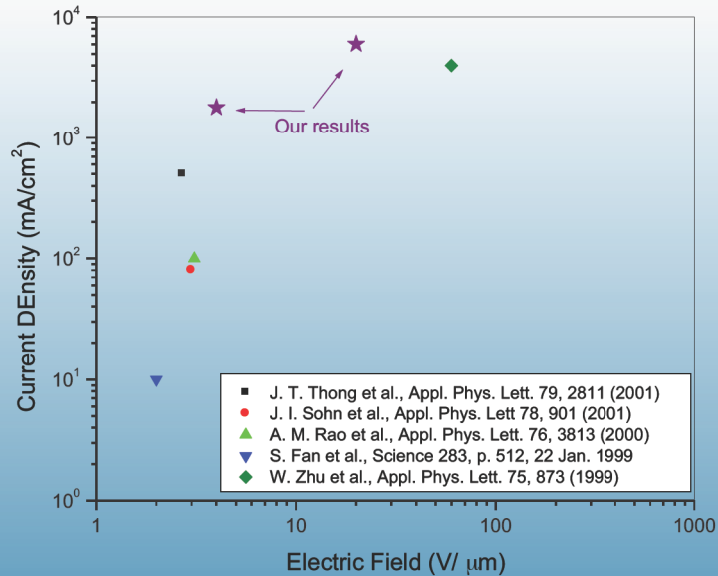
CNT bundles of $1\text{--}2\ \mu\text{m}$ diameter spaced $5\ \mu\text{m}$ edge-to-edge produced the highest field emission current.

This arrangement is being used in multiple applications routinely producing 2 to $10\ \text{A}/\text{cm}^2$ current density at low fields of 4 to $8\ \text{V}/\mu\text{m}$

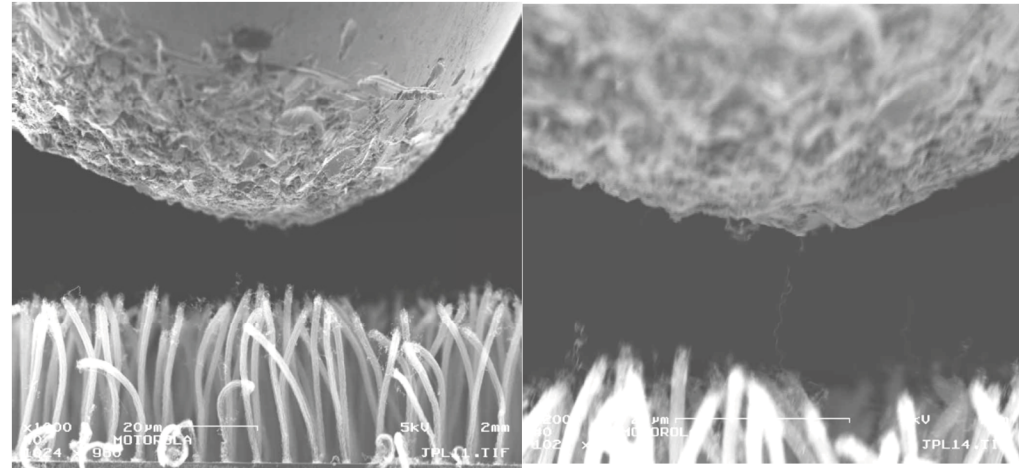
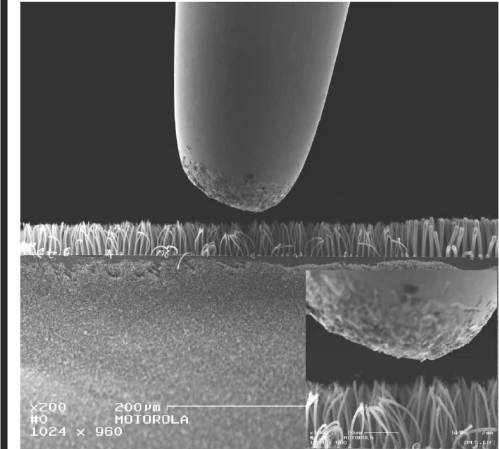
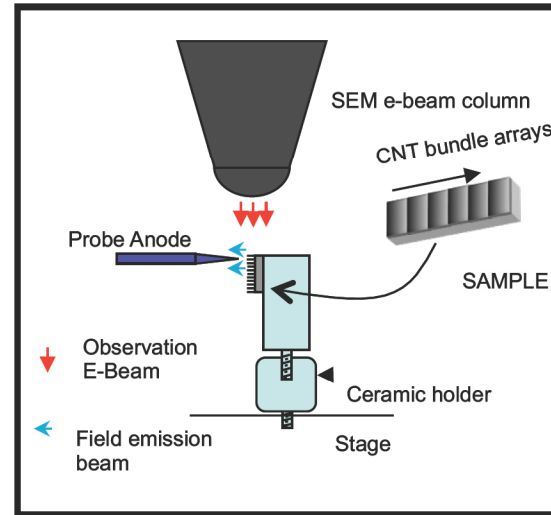


FIELD EMISSION OF ELECTRONS

Repeatable High Current Density



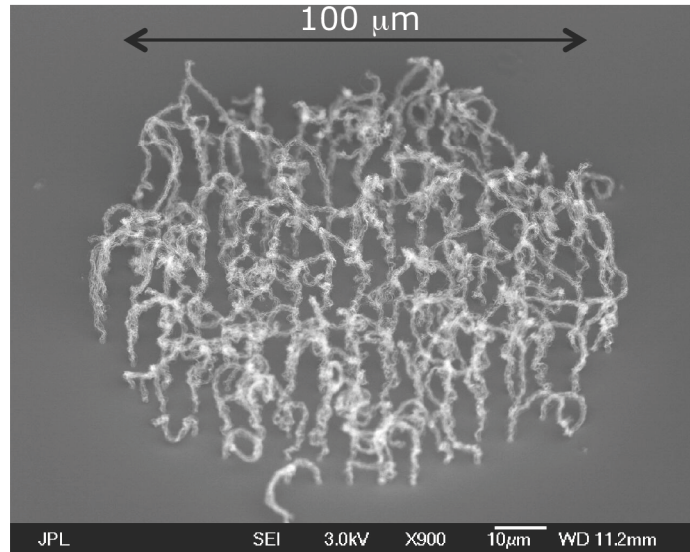
Our results correspond to
 $100\ \mu\text{m} \times 100\ \mu\text{m}$ area.



Experiments at Motorola Research Lab., Phoenix, AZ
{Thanks to Drs. Ken Dean, Lyndee Tissinger, & Scott Johnson}

FIELD EMISSION OF ELECTRONS

Repeatable High Current Density



1 μm diameter – 5 μm edge-to-edge space

CNTs on all samples are 10 to 20 μm tall

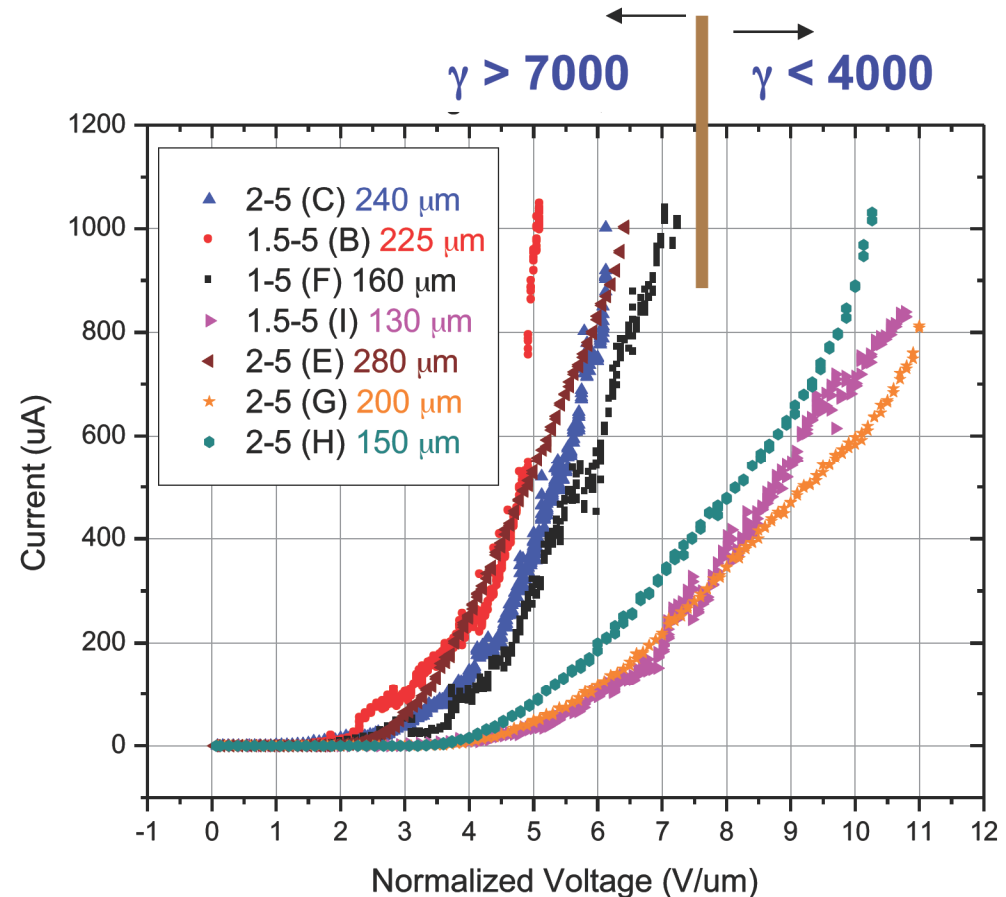
Range of Current Density

10 to 15 A/cm²

Vacuum = 2×10^{-5} Torr

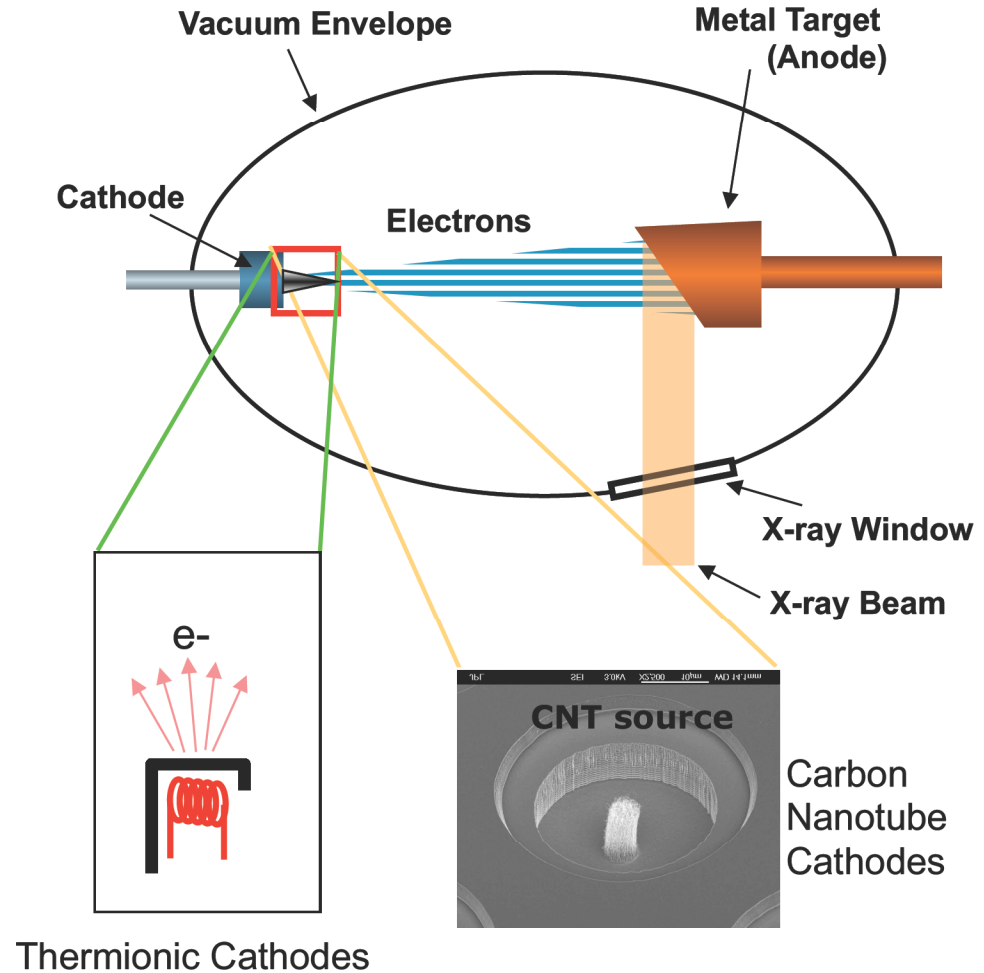
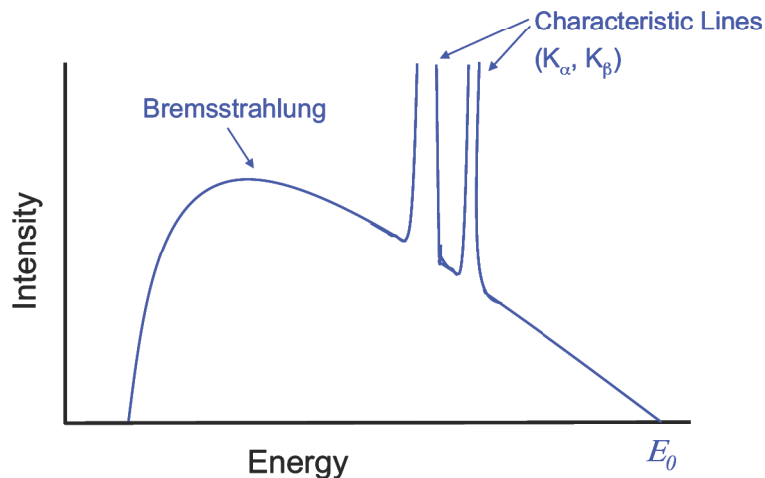
1 mA = 12.7 A/cm²

785 μA = 10 A/cm²



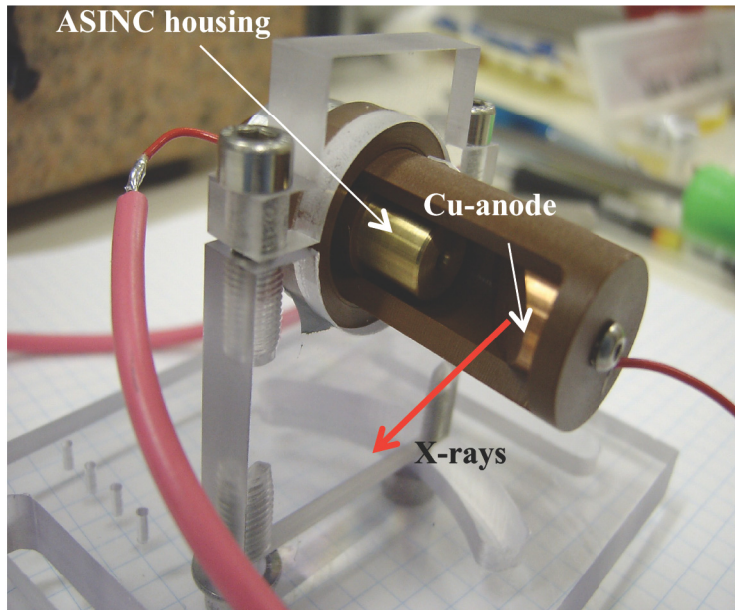
APPLICATION 1: MINIATURE X-RAY TUBE

- Accelerated electrons bombard with a metal target to produce a continuous X-ray spectrum (Bremsstrahlung) as well as characteristic X-ray lines.
- The upper limit of the Bremsstrahlung radiation energy is limited by the acceleration voltage (Duane-Hunt Law).



APPLICATION 1: MINIATURE X-RAY TUBE

CNT X-ray Tube



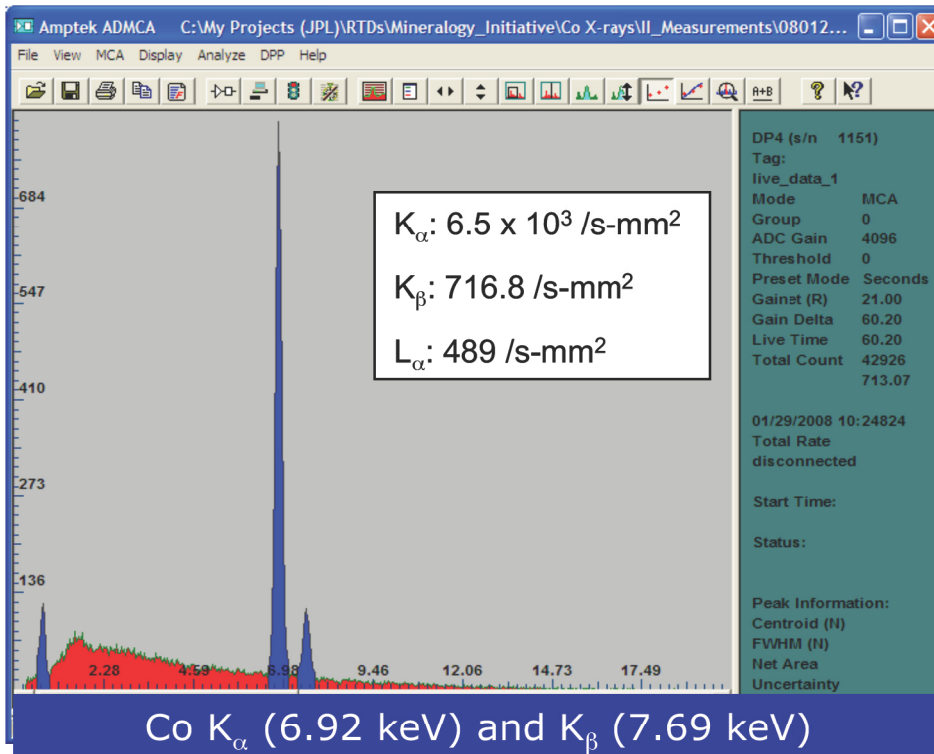
- ~ 5 cm long and ~ 1 cm in diameter
- Uses shaped **Cobalt or Copper** anode
- CNT bundle arrays are mounted on a screw-on platform
- Operates between **15 kV to 20 kV** acceleration voltage
- Emitted current at the cathode is in the range of **15 μ A to 50 μ A**
- Max. photon flux produced so far **$\sim 8.8 \times 10^4$ /s**
(1-mm ϕ aperture)

Emission Efficiency

$$\eta = I_A / I_K$$

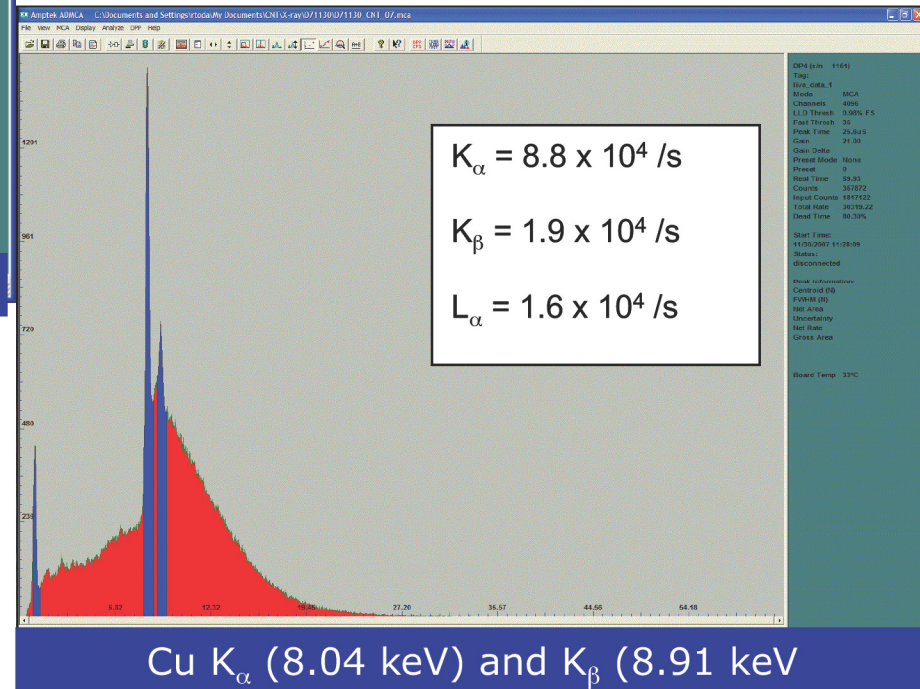
APPLICATION 1: MINIATURE X-RAY TUBE

X-ray Source Spectra



$I_A \sim 3 \mu\text{A}$ ($\eta \sim 20\%$); $V_A \sim 20.0$ kV; $V_G = 2$ kV; Measured photon fluxes through a 200- μm ϕ collimator are shown in the inset.

$I_A \sim 15 \mu\text{A}$ ($\eta \sim 30\%$); $V_A \sim 16.4$ kV; Measured photon fluxes through a 1-mm ϕ collimator are shown in the inset.



APPLICATION 2: “DIGITAL” VACUUM MICROELECTRONICS



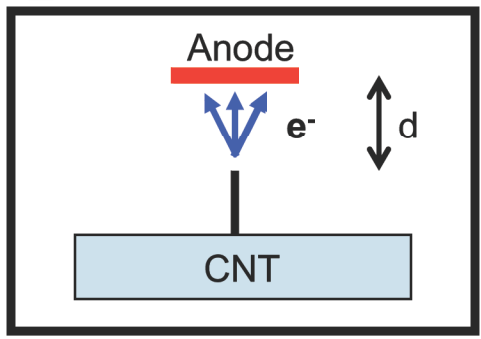
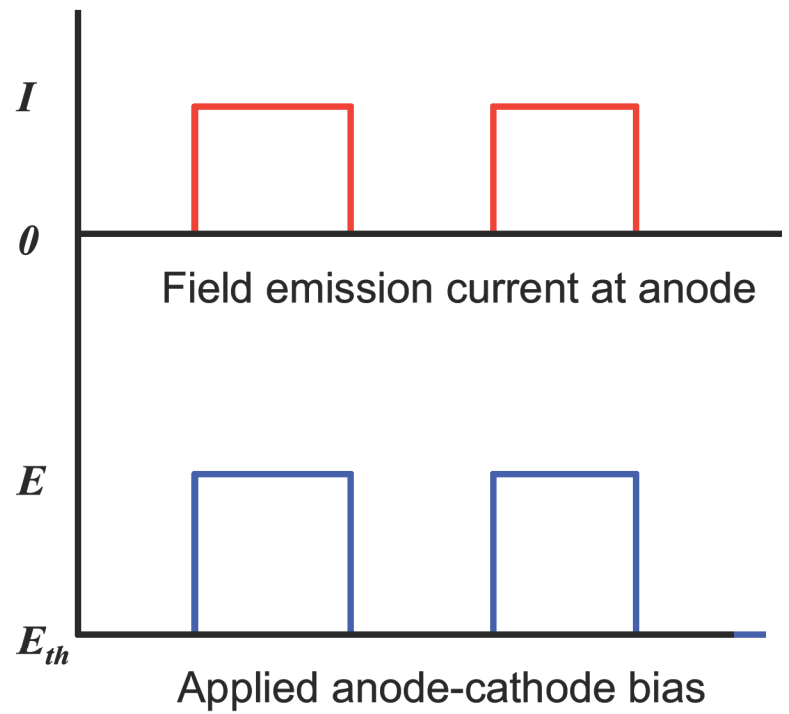
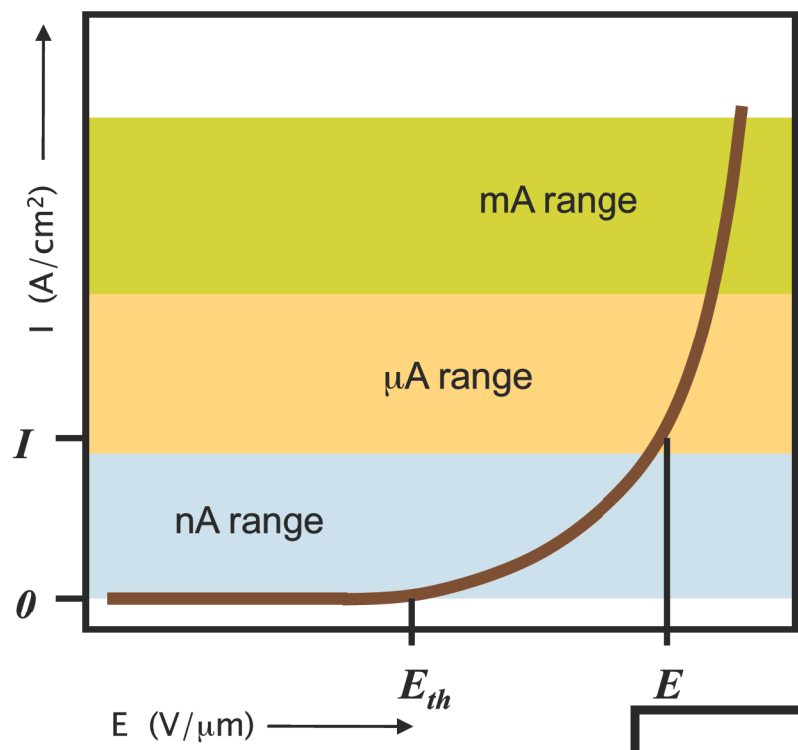
- To fulfill the need for extreme environment electronics (350-700° C and radiation insensitive)
- State-of-the-art: Solid-State devices; demonstrated up to 500° C and tens of Mega Rads (limited component demonstrations)
- NEMS computational components demonstrated up to 600° C (Case Western)
- JPL technology: “Digital” Vacuum Microelectronics – *programmable logic gate demonstrated at 700° C (DC switching) **First of its kind device demonstrated.***
 - Turning the “clock” back a “bit” to the tube days; merging micromachining, nanotube field emission and vacuum packaging techniques.
- **Why vacuum microelectronics?** *Electron transport is in vacuum-inherently radiation insensitive and high-temperature tolerant.*



“DIGITAL” VACUUM ELECTRONICS

The Concept

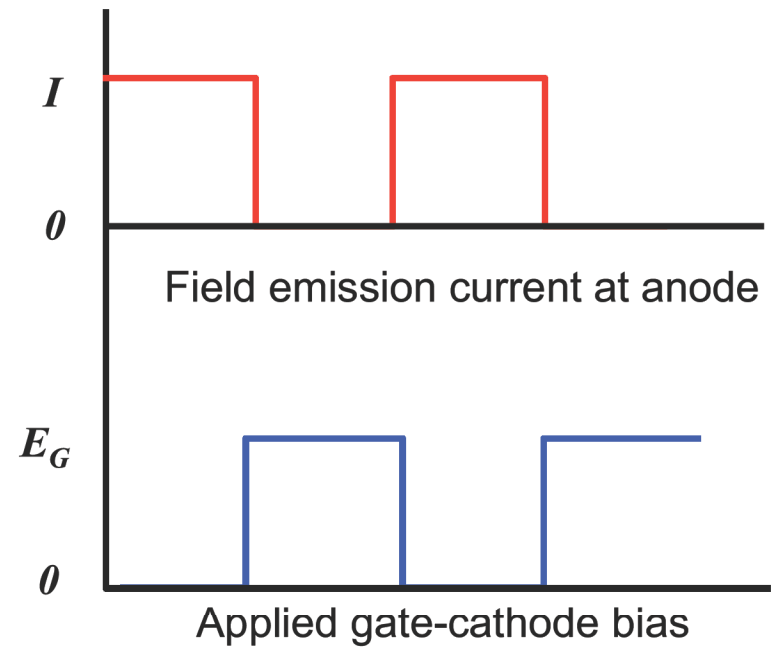
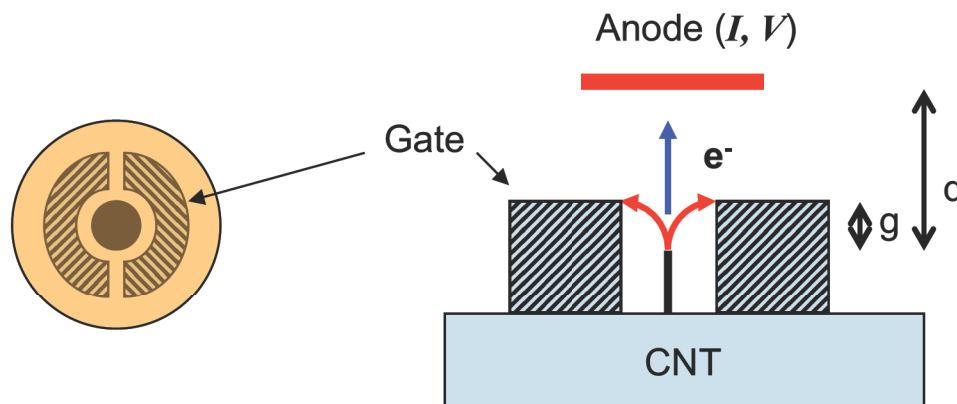
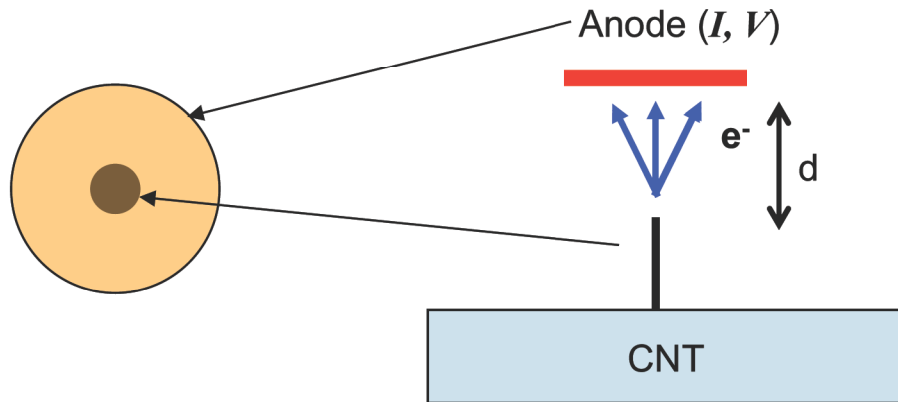
Typical Field Emission Curve



$$E = V / d$$

“DIGITAL” VACUUM ELECTRONICS

The Concept



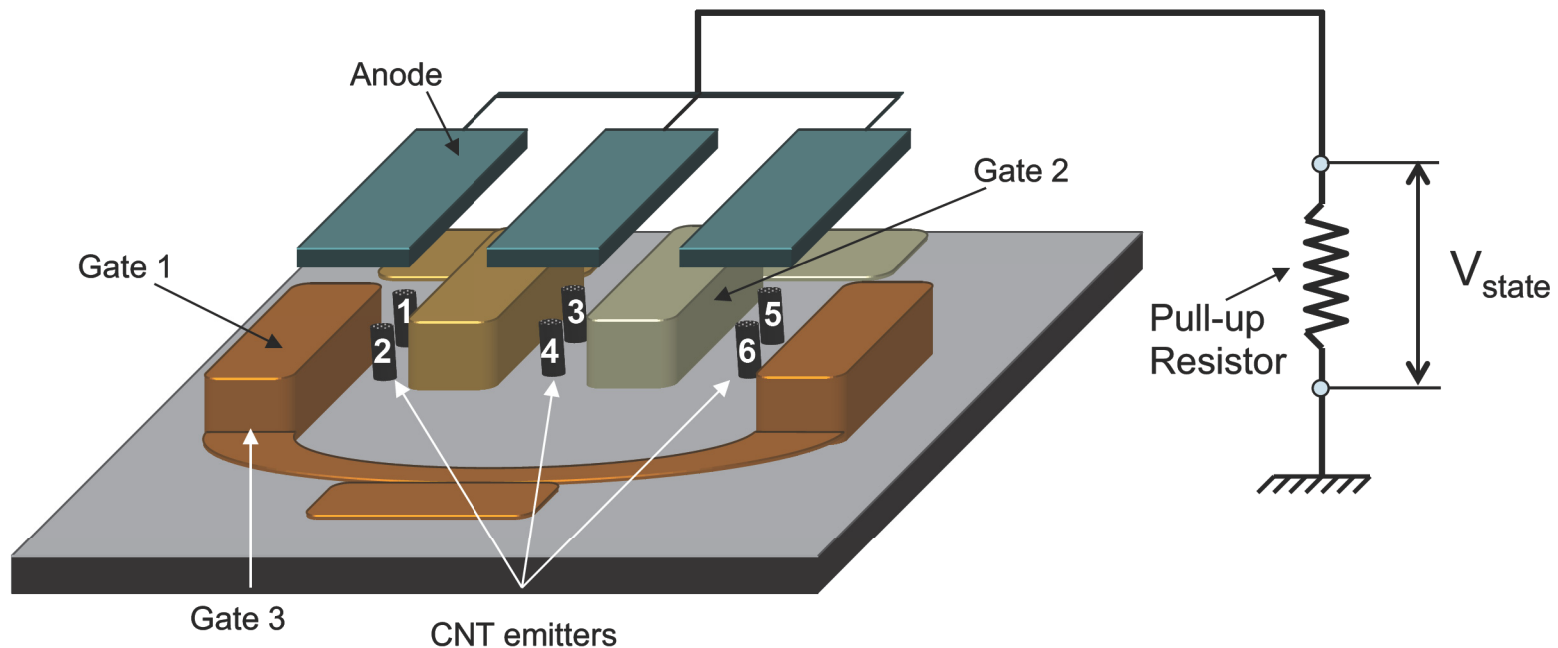
$$d > g$$

$$V_G = V$$

$$E_G > E > E_{th}$$

INVERSE MAJORITY GATE (IMG)

Sketch of the Device

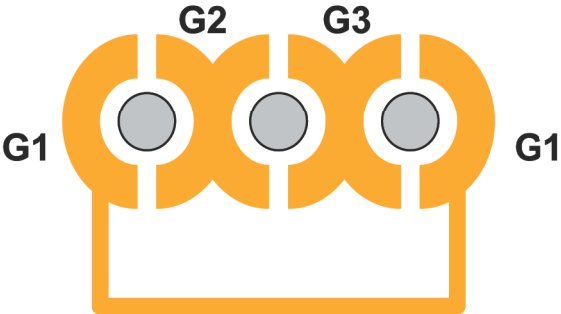


The operation of this device is shown schematically in the next slide.



INVERSE MAJORITY GATE (IMG)

Operation



Gate bias OFF



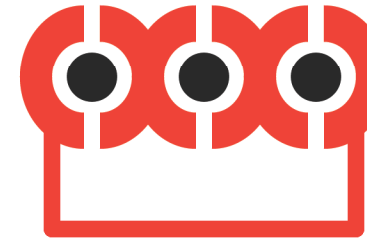
CNT emitting to anode



Gate bias ON



CNT NOT emitting to anode



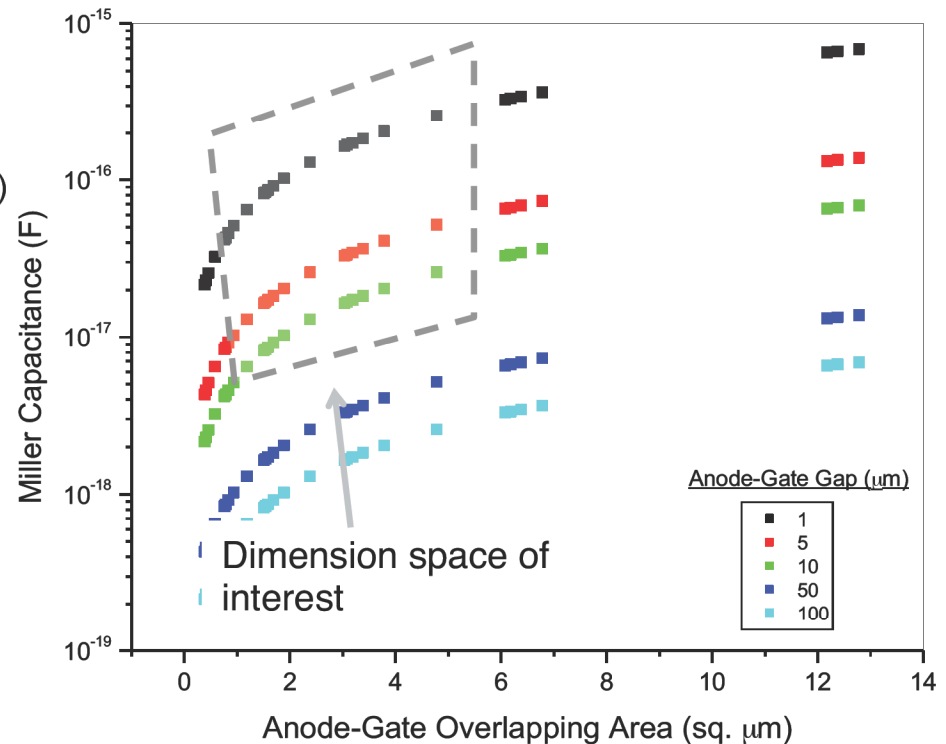
INVERSE MAJORITY GATE (IMG)

Truth Table

Sl.No.	Gate 1	Gate 2	Gate 3	O/P
1	0	0	0	1
2	1	0	0	1
3	0	1	0	1
4	1	1	0	0
5	0	0	1	1
6	1	0	1	0
7	0	1	1	0
8	1	1	1	0

*The output indicates a combination
of NAND and NOR gates*

Miller Capacitance Calculation



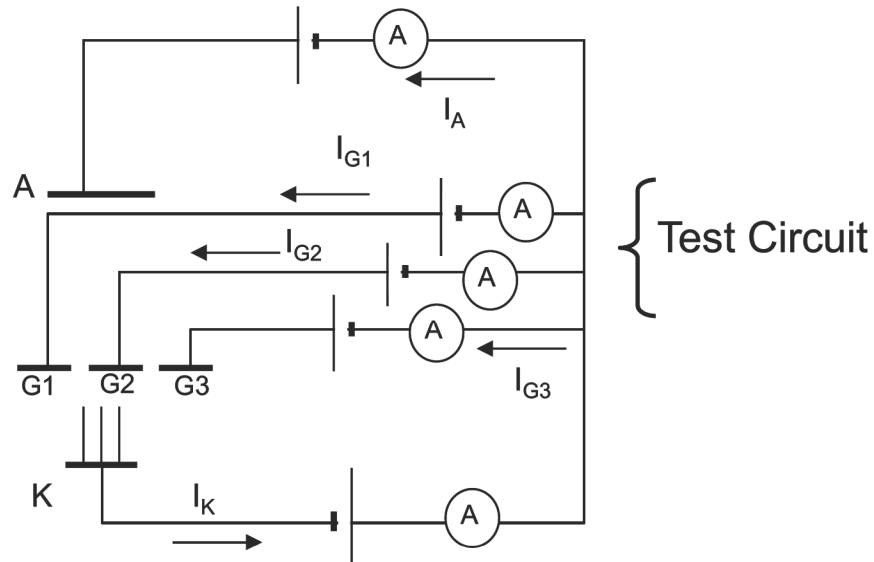
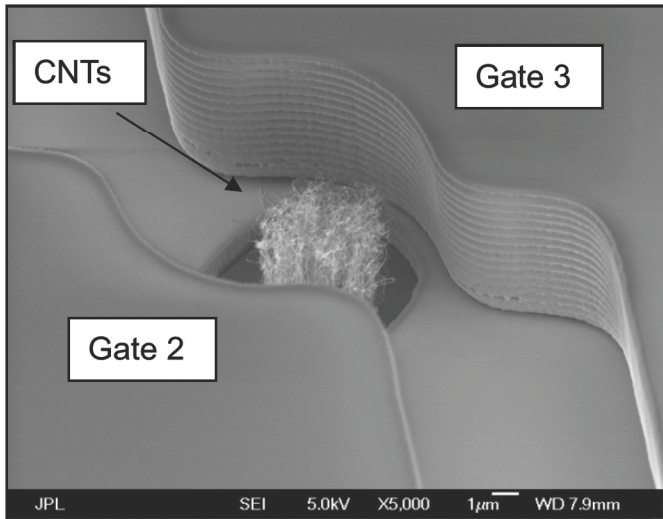
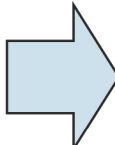
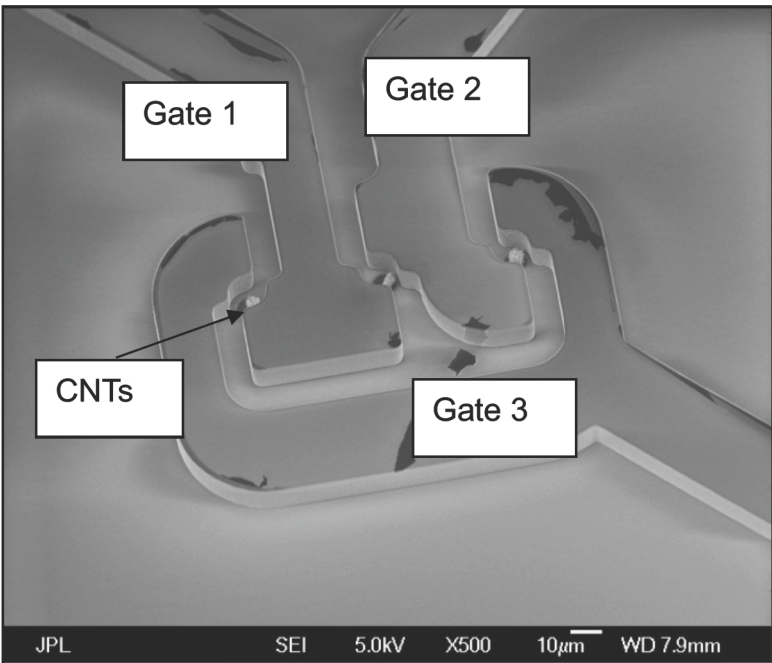
Smaller line widths allow vacuum devices to achieve similar device densities as those possible by solid state devices

For a Full Adder	Solid State (0.18 μm process)	Solid State (0.09 μm process)	IMG-based (0.5 μm process)
Footprint (μm)	13.86 x 5.4	8.12 x 2.52	18 x 4



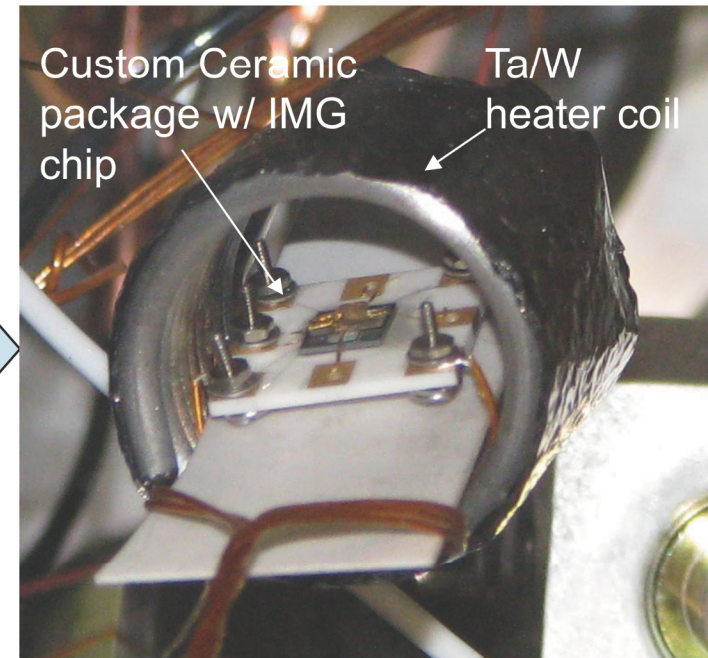
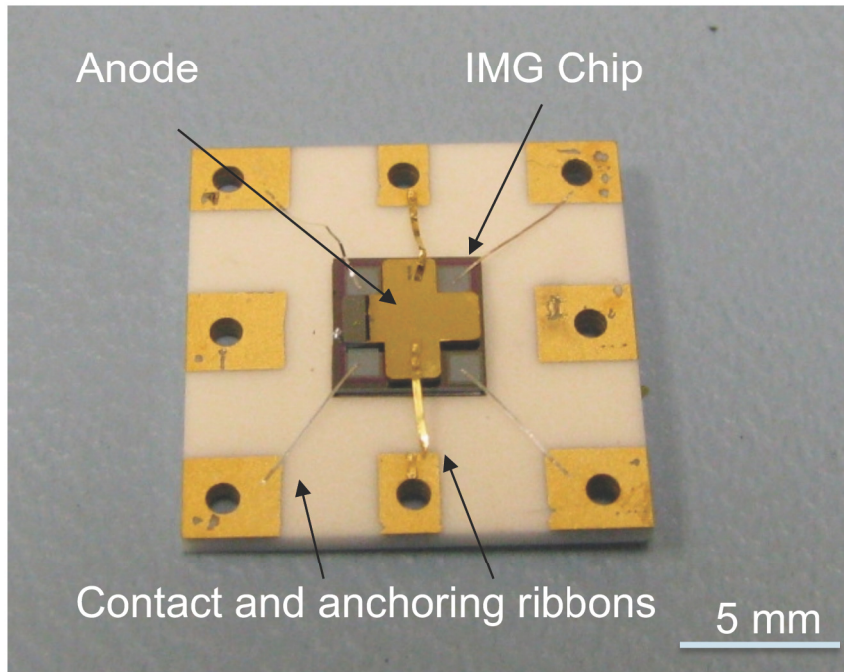
IMG DEVICES

SEM Micrographs



HIGH TEMPERATURE TESTS

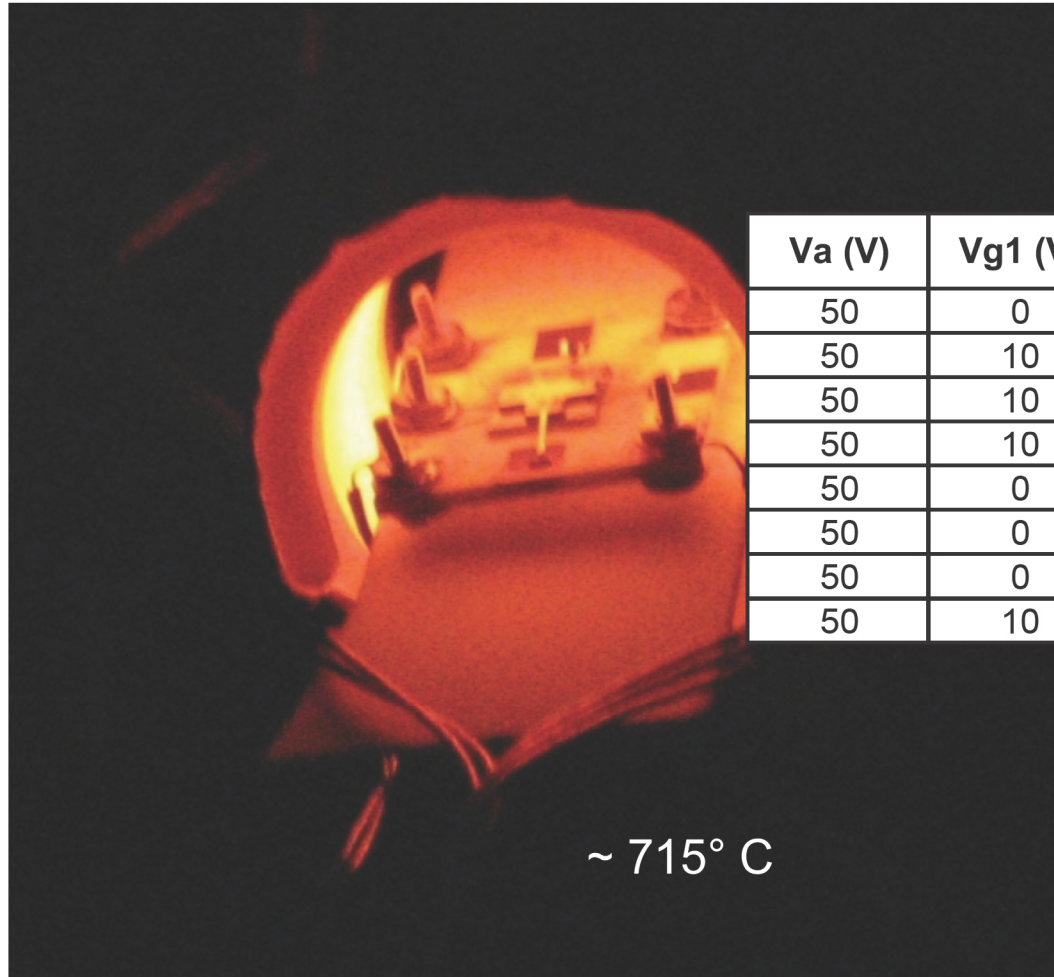
IMG Device Test Setup



**Ceramic IMG chip mount with
cross-shaped anode placed
on top**

HIGH TEMPERATURE TESTS

High Temperature Test Results (DC)



**Successful three-gate
operation**

Va (V)	Vg1 (V)	Vg2 (V)	Vg3 (V)	Ia (nA)	O/P State
50	0	0	0	3.2	1
50	10	0	0	2.8	1
50	10	10	0	0.7	0
50	10	10	10	0	0
50	0	10	0	3.6	1
50	0	10	10	0.27	0
50	0	0	10	2.5	1
50	10	0	10	0.35	0

***Is the current contribution
only from field emission?***

***Is there a significant
thermionic effect?***

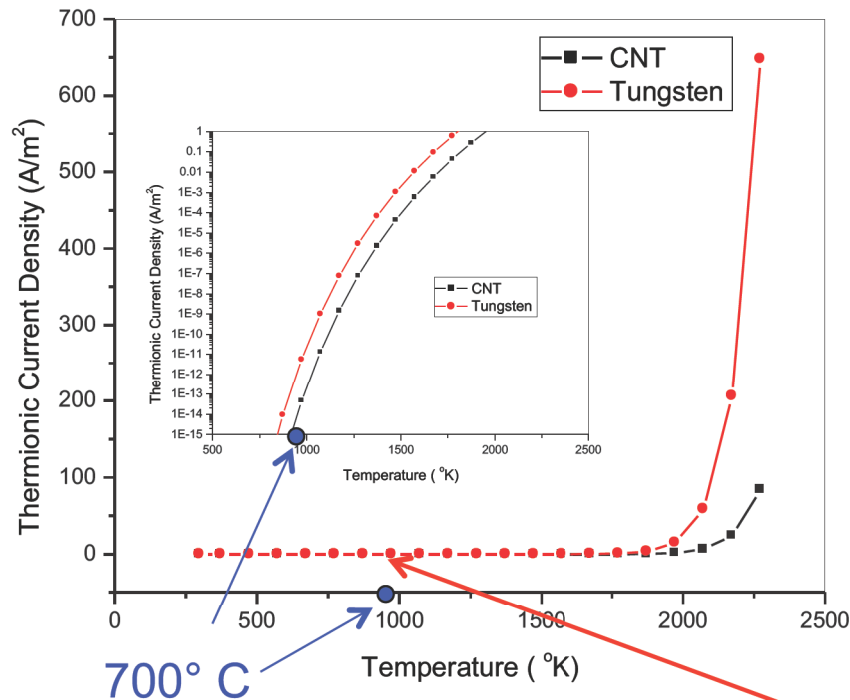
HIGH TEMPERATURE TESTS

Effect of Thermionic Emission

Richard-Dushman relation:

$$J(T) = A_R T^2 e^{-\left(\frac{\phi}{k_B T}\right)}$$

Where, $A_R = \frac{4\pi \cdot e \cdot m_e k_B^2}{h^3}$



$J(T)$ = Thermionic current density (A/m^2)

A_R = A constant

T = Temperature ($^{\circ}K$)

e = electron charge (Coulomb)

m_e = electron mass (kg)

k_B = Boltzman constant

h = Planck' s constant

At 700° C the thermionic emission contribution from CNTs over the area of the bundle (2- μm diameter) is negligible.



PERFORMANCE ESTIMATION

Frequency of Operation Relationships

Upper limit of frequency of operation is influenced by:

transconductance (g_m)

inter-electrode capacitances (C_{G-K} and C_{G-A})

input and output impedances

$$f_T = g_m / 2 \pi (C_{G-K} + C_{G-A}); \text{ cut-off frequency}$$

The best frequency of operation in micron scale vacuum devices is defined by the transit time of electrons from cathode to an electrode.

$$\tau = d (2 m_e / \varepsilon)^{0.5};$$

This is a simplified equation that ignores the effect of space-charge on the transit time. That effect counters τ as d is decreased.

d = cathode-electrode gap (m)

m_e = mass of electron (kg)

ε = energy (J) – a function of applied field

The transit time limited frequency is the highest achievable because the medium of transport is vacuum and the physical dimensions involved are small.

$$f_{max} = 1 / \tau$$

For example, transit time limited frequency of operation for a diode with anode-cathode gap of 5 μm , applied voltage of 10 V is **187 GHz**.

SUMMARY



- High performance CNT field emitters have been developed with improved adhesion to the substrate for high-field operation.
- Specific space instrument applications are being developed using these field emitters such as miniature X-ray tubes, and high-temperature, radiation-insensitive computational electronics.
- Miniature X-ray tube operation has been demonstrated.
- Inverse Majority Gate (IMG) devices based on vacuum electronic principle were designed, fabricated, and tested at room temperature and at high temperatures up to 700° C.
- Estimation show that these devices are capable of switching in the GHz range.
- Our analysis shows that by controlling the device dimensions (using direct e-beam write or a stepper) we can make these devices virtually transit time limited in switching speeds. Numbers in the range of tens to hundreds of GHz have been calculated.
- Packaging and material issues are important to be addressed for 700° C applications.